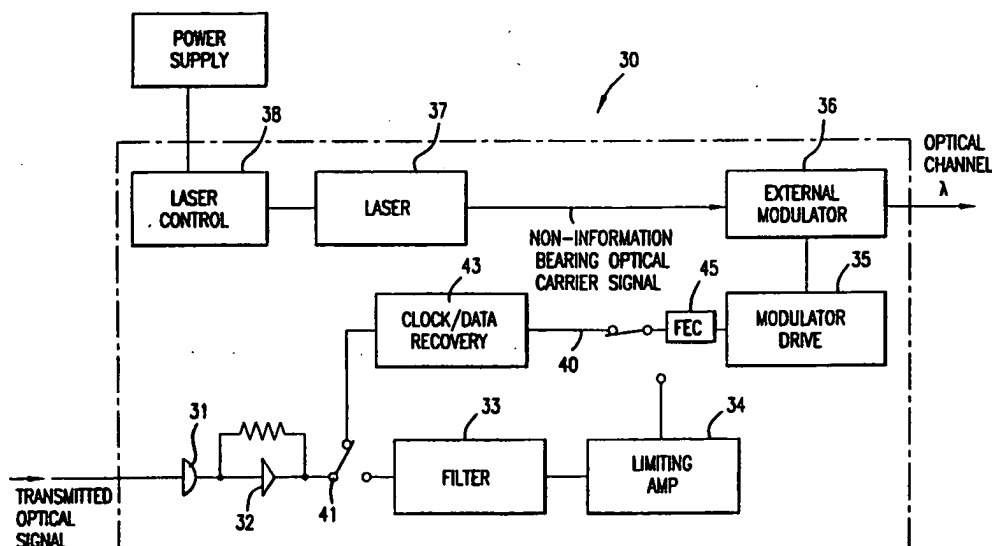




## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> : H04J 14/02, H04B 10/16, H04L 1/00		A1	(11) International Publication Number: WO 99/21316
			(43) International Publication Date: 29 April 1999 (29.04.99)
(21) International Application Number: PCT/US98/22273		(81) Designated States: AU, CA, CN, JP, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).	
(22) International Filing Date: 21 October 1998 (21.10.98)			
(30) Priority Data: 08/955,058      21 October 1997 (21.10.97)      US		Published <i>With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i>	
(71) Applicant: CIENA CORPORATION [US/US]; Legal Dept., 920 Elkridge Landing Road, Linthicum, MD 21090 (US).			
(72) Inventors: ALEXANDER, Stephen, B.; 313 Locust Thorn Court, Millersville, MD 21108 (US). CHADDICK, Steve, W.; 739 Harness Creek View Drive, Annapolis, MD 21403 (US). LITZ, Roy, C.; 2613 Beckleysville Road, Freeland, MD 21053 (US). SMITH, Cecil, D.; 626 Cypress Point Drive, Severna Park, MD 21403 (US).			
(74) Agents: DAISAK, Daniel, N. et al.; Ciena Corporation, Legal Dept., 1201 Winterson Road, Linthicum, MD 21090 (US).			

(54) Title: REMODULATORS FOR WDM OPTICAL COMMUNICATION SYSTEMS



## (57) Abstract

The present invention provides a remodulating channel selector for a wavelength division multiplexed optical communication system. The remodulating selector receives a WDM input signal, selects a particular optical channel from the WDM signal and places the information from the selected signal onto a newly-generated optical output signal. The wavelength of the output optical signal can be the same as or different from one of the optical channels which comprises the WDM input signal. When used in a WDM optical communication system with remodulators at the transmission input, the remodulating selectors provide complete control over the interfaces with optical transmitters and receivers, permitting use with a broad range of optical equipment. FEC is provided at remodulators.

**FOR THE PURPOSES OF INFORMATION ONLY**

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakhstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

## REMODULATORS FOR WDM OPTICAL COMMUNICATION SYSTEMS

**FIELD OF THE INVENTION:**

- 5           The invention relates to wavelength division multiplexed optical communications generally and, more particularly, to remodulating channel selectors for selecting a particular channel wavelength and placing the information from that channel wavelength onto a newly generated optical channel.

10   **BACKGROUND OF THE INVENTION:**

- Optical communication systems are a substantial and fast-growing constituent of communication networks. The expression "optical communication system," as used herein, relates to any system which uses optical signals to convey information across an optical waveguiding medium. Such optical systems include, but are not limited to,
- 15   telecommunications systems, cable television systems, and local area networks (LANs). Optical systems are described in Gowar, Ed. Optical Communication Systems, (Prentice Hall, NY) c. 1993, the disclosure of which is incorporated herein by reference. Currently, the majority of optical communication systems are configured to carry an optical channel of a single wavelength over one or more optical waveguides. To convey information
- 20   from plural sources, time-division multiplexing is frequently employed (TDM). In time-division multiplexing, a particular time slot is assigned to each signal source, the complete signal being constructed from the portions of the signals collected from each time slot. While this is a useful technique for carrying plural information sources on a

single channel, its capacity is limited by fiber dispersion and the need to generate high peak power pulses.

While the need for communication services increases, the current capacity of existing waveguiding media is limited. Although capacity may be expanded e.g., by  
5 laying more fiber optic cables, the cost of such expansion is prohibitive. Consequently, there exists a need for a cost-effective way to increase the capacity of existing optical waveguides.

Wavelength division multiplexing (WDM) has been explored as an approach for increasing the capacity of existing fiber optic networks. In a WDM system, plural optical  
10 signal channels are carried over a single waveguide, each channel being assigned a particular wavelength. Through the use of optical amplifiers, such as doped fiber amplifiers, plural optical channels are directly amplified simultaneously, facilitating the use of WDM systems in long-distance optical networks.

To provide compatibility of WDM systems with existing networks, it is desirable  
15 to convert a signal from a received transmission wavelength from a customer to a specific channel wavelength within the WDM system. This is particularly true in WDM systems employing many channels, often referred to as "dense" WDM, where channel spacings are on the order of one nanometer or less. Such WDM systems require precise control of the optical signal wavelength for each channel in order to avoid "crosstalk," i.e.,  
20 interference between adjacent channels. A WDM optical system for converting signals from received transmission wavelengths to specific channel wavelengths using optical remodulators is described in U.S. Patent 5,504,609, the disclosure of which is incorporated by reference. A WDM optical system which uses both remodulators and

diverse optical sources (e.g., to accommodate signals which are generated at the proper channel wavelength or optical channels being routed from another optical path) is described in parent application Serial Number 08/624,269, the disclosure of which is incorporated by reference, above.

5           While both the described approaches advantageously offer compatibility with existing optical communication systems, particularly those systems using SONET terminal receivers which conform to the SONET "long-haul" standard, i.e., terminals configured to detect low optical signal levels, it would be desirable to provide an output channel signal conforming to SONET "short-reach" interface standards, i.e., terminals  
10 configured to detect higher-level optical signals.

Previously, attention has been focused on conversion of a single transmission channel from a wavelength outside the wavelength band amplified by optical amplifiers to a wavelength within the wavelength band amplified by optical amplifiers and then back to the original transmission wavelength for reception by an optical receiver. U.S. Patent No.  
15 5,267,073 describes wavelength conversion in a conventional single channel optical system to enable signal amplification by optical amplifiers. In the patent, an adapter is provided to receive a transmission optical signal having a wavelength which is outside the operating parameters of the optical amplifier. The signal is supplied to an optical-to-electronic converter module. The resultant electrical signal is output to an adjusting  
20 means comprising a laser piloting circuit for directly modulating a signal laser. The output of the signal laser is subsequently amplified by an optical amplifier. At the receive end, an adapter is provided to convert the optical signals from the amplifier into electrical signals which are fed to an adjustment module. The adjustment module comprises a laser

piloting circuit which controls a laser transmitter. In this manner, the patent purports to avoid problems in which normal optical line receivers have problems with frequency response when they are coupled to optical amplifiers in optical fiber lines.

There is a need in the art for WDM channel selectors which can both select a  
5 particular channel wavelength from a multiplexed optical signal and place the information from that channel onto a newly-generated optical signal, the optical signal selected to have the desired characteristics which make it compatible with the selected terminal receiver equipment. Such channel selectors would permit the use of less expensive terminal equipment, facilitating the use of wavelength division multiplexing in a greater  
10 variety of telecommunications applications.

#### SUMMARY OF THE INVENTION

The present invention provides a remodulating channel selector for a wavelength division multiplexed optical communication system. The remodulating selector receives  
15 a WDM input signal, selects a particular optical channel from the WDM signal, and places the information from the selected signal onto a newly-generated optical output signal. The remodulating selector typically comprises an optical input port configured to receive a wavelength division multiplexed optical communication signal from a wavelength division multiplexed optical communication system. An optical channel  
20 selector optically communicates with the optical input port to select a single optical channel from the WDM input signal. An optical-to -electrical converter optically communicates with the optical channel selector to receive the selected channel and output an electrical signal which corresponds to information from the selected optical channel. This information is placed onto an optical signal created by an optical signal emitter such

as a laser or light-emitting diode (LED). When used in a WDM optical communication system with remodulators at the transmission input, the remodulating selectors provide complete control over the interfaces with optical transmitters and receivers, enabling a WDM system to interface with a broad range of optical transmitting and receiving  
5 equipment.

**BRIEF DESCRIPTION OF THE DRAWINGS:**

FIG. 1 schematically depicts an optical communication system employing remodulating channel selectors according to the present invention.

10 FIG. 2 schematically depicts a remodulator used in the optical communication system of FIG. 1.

FIG. 3 illustrates a block diagram of a forward error correction encoder in accordance with the present invention.

15 FIG. 4 schematically depicts a remodulating channel selector used in the optical communication system of FIG. 1.

FIG. 5 illustrates a block diagram of a forward error correction decoder in accordance with the present invention.

**DETAILED DESCRIPTION:**

20 Turning to the drawings in detail in which like reference numerals indicate the same or similar elements in each of the several views, FIG. 1 depicts an optical communication system 10 according to an embodiment of the present invention. Optical communication system 10 operates to take optical transmission signals from diverse optical transmitters and other optical signal sources and map the signal sources onto a

wavelength division optical communication system, i.e., a communication system in which individual optical signals correspond to optical channels within a wavelength division multiplexed optical signal carried on an optical waveguide. Optical communication system 10 includes a first set of one or more optical transmitters 22, 24, 5 each optical transmitter emitting an information-bearing optical signal at a first transmission wavelength.

Optical transmitters 22 and 24 generally include a laser, such as a DFB semiconductor laser, and a modulator for creation of an information-bearing optical transmission signal. In an exemplary embodiment, optical transmitters 22 and 24 are 10 SONET OC-48 transmitters. When plural optical transmitters are provided, the transmission wavelength of each transmitter can be the same or different. Because transmitters 22 and 24 may form part of an existing optical system, a wide variety of transmitters emitting in a broad range of wavelengths can be accommodated in the optical communication system of the present invention, thus ensuring compatibility with 15 currently-deployed transmission equipment. Typical transmission elements emit wavelengths ranging from about 1300 to 1600 nm. Transmission elements in current optical communication systems and various optical modulation techniques employed therein are described in Gowar, Optical Communication Systems, incorporated by reference above. In the depicted exemplary embodiment, optical transmitter 22 is a 1310 20 nm optical transmitter and optical transmitter 24 is a 1550 optical transmitter, commercially available from NEC, Fujitsu, Alcatel, and Nortel.

Optical communication system 10 includes a plurality of remodulators 30 for receiving the transmitted information-bearing optical signal at transmission wavelength



from the first set of optical transmitters and transmitting an information-bearing optical signal at a WDM optical system channel wavelength. The expression "information - bearing optical signal," as used herein, refers to an optical signal which has been coded with information, including, but not limited to, audio signals, video signals, and computer data, generally through modulation. Similarly, the expression "non-information-bearing optical signal," as used herein, relates to a CW optical signal which has not been coded with information, e.g., an optical carrier which has not been modulated. Typically, the wavelengths emitted by the remodulators are selected to be within the 1500 nanometer range, the range in which the minimum signal attenuation occurs for silica-based fibers.

More particularly, the wavelengths emitted by the remodulators are selected to be in the range from 1530 to 1560 nanometers. However, other wavelength bands may be selected according to overall system requirements.

For a 16-channel wavelength division multiplexed optical communication system, an exemplary channel plan is set forth in Table 1 below. The optical channel plan dictates both the wavelengths of the optical remodulators and the corresponding wavelengths selected by the wavelength selectors in the optical receiving systems.

**Table 1**

<b>Channel Number</b>	<b>Wavelength (nm)</b>
1	1557.36
2	1556.56
3	1555.75
4	1554.94
5	1554.13
6	1553.33
7	1552.52
8	1551.72
9	1550.92

10	1550.12
11	1549.32
12	1548.51
13	1547.72
14	1546.92
15	1546.12
16	1545.32

Wavelength division multiplexed topical communication system 10 optionally includes a second set of one or more optical transmitters 25 which directly output an optical signal having a wavelength which corresponds to an optical channel within the channel plan of the communication system. Consequently, optical transmitters 25 optically communicate with optical multiplexer or combiner 50 without the need for remodulation by remodulators 30. Optical transmitters 25 are commercially available from a variety of suppliers, including the OCT-204 series of optical transmitters from Alcatel, the HT2H-LR1H optical transmitters from Fujitsu, and the ITS-2400 optical transmitters from NEC.

Wavelength division multiplexed optical communication system 10 further optionally comprises additional sources of optical signals, e.g., optical signals from add/drop multiplexers or demultiplexers from other optical systems. Examples of various configurations of WDM optical systems with diverse signal sources are described in the parent application, incorporated by reference above.

An exemplary remodulator 30 for use in optical communication system 10 is schematically depicted in FIG. 2. In remodulator 30, the transmitted optical signal is converted by electro-optical converter 31, typically a photodiode, to an electrical signal. The electrical signal is amplified by transimpedance amplifier 32, passed through filter 33

to limit the noise bandwidth and waveshape the signal, and further amplified by limiting amplifier 34. Optionally, remodulator 30 can include clock and data recovery circuit 40 for use with high data rate signals. Switch 41 automatically selects high data rate signals and passes them through clock/data recovery element 43. The selected signals are  
5 retimed, advantageously reducing jitter. The retimed signal exits clock and data recovery circuit through switch 42.

The resultant electrical signal is used to drive external modulator 36 through modulator driver 37. As used herein, the expression "external modulator" includes any modulator which acts on an optical carrier emitted from a continuous wave (CW) optical  
10 source, such as a laser. Such external modulators can be packaged with the optical source or packaged separately from the optical source.

Remodulator 30 also includes a optical source, such as laser 37, for delivering a non-information-bearing optical carrier signal to laser output waveguide 39. In an exemplary embodiment, laser 37 is a DFB semiconductor diode laser, generally  
15 comprising one or more III-V semiconductor materials, commercially available from a wide variety of suppliers such as Fujitsu, GEC Marconi, Alcatel, and Hewlett-Packard. The laser outputs an optical carrier signal at a particular channel wavelength, the wavelength corresponding to a channel selector wavelength included in the remodulating channel selector. Laser control 38 provides the required laser bias current as well as  
20 thermal control of the laser. Using thermal control, the precise operating wavelength of the laser is maintained, typically to within a one angstrom bandwidth.

External modulator 36 acts on the optical carrier signal output from laser 37, as opposed to acting on the laser itself or on a laser driver, as occurs in direct modulation

systems. An exemplary external modulator employs a waveguiding medium whose refractive index changes according to the applied electrical field, i.e., a material exhibiting an electro-optic effect. Consequently, the phase of input optical carrier signals is altered as a result of the changing refractive index of the optical waveguide. A suitable electro-optic waveguiding material for the external modulators of the present invention is lithium niobate,  $\text{LiNbO}_3$ . An exemplary electro-optic modulator for use as external modulator 36 is a Mach-Zehnder interferometric modulator which provides high-speed intensity modulation of optical carriers. In the Mach-Zehnder configuration, two optical paths are provided. An incoming optical carrier is split between the two paths of the interferometer. At least one path of the interferometer is phase modulated. When the signal is recombined at the output, the light from the paths either constructively or destructively interferes, depending upon the electrical field applied to the surrounding electrodes during the travel time of the carrier, creating an amplitude-modulated output signal. Further details of electro-optic modulators are described in Becker, "Broad-Band Guided Wave Electrooptic Modulators," IEEE Journal of Quantum Electronics, Vol. QE-20, No. 7, July, 1984, pp. 723-727, the disclosure of which is incorporated by reference herein. Mach-Zehnder interferometers suitable for use in external electro-optic modulator 36 are commercially available from United Technologies, and IOC. The modulated output signal is the information-bearing optical channel whose wavelength corresponds to a particular channel selector wavelength in the optical communication system.

Alternatively, the external modulator employed in the remodulators of the present invention can be selected from electro-absorption external modulators. Electro-absorption modulators function by changing the bandgap of the modulating material to

impart information to the optical carrier signal. Exemplary electro-absorption modulators are described in Wood, "Multiple Quantum Well (MQW) Waveguide Modulators," Journal of Lightwave Technology, Vol. 6, No. 6, June, 1988, pp. 743-757, the disclosure of which is incorporated by reference herein.

5           Optionally, remodulators 30 include forward error correction (FEC) encoders 45. The addition of forward error correction to a WDM optical communication system advantageously decreases the bit error rate (BER) by adding redundancy, e.g., coding bits, to the individual optical channels which comprise the WDM signal. In particular, the addition of FEC permits the WDM system to achieve substantially error-free performance  
10 in the presence of the nonlinearities present in optical communication system. At the receive end, a forward error correction decoder examines the coding bits to accurately reconstruct the transmitted information. A variety of coding algorithms may be used to accomplish forward error correction in the WDM optical systems of the present invention. Exemplary algorithms are convolutional encoding with threshold decoding, Viterbi  
15 decoding, or Reed-Solomon encoding/decoding. Detailed descriptions of these and other coding algorithms are found in Wiggert, Error-Control Coding and Applications, (Artech House, c. 1978), the disclosure of which is incorporated by reference herein.

Advantageously, forward error correction in the WDM optical systems of the present invention enables a "channel trace" function that encodes the channel ID, source,  
20 and destination into a small overhead bit stream which would permit the remodulating channel selector to respond only to an incoming signal with the proper addressing. The use of channel tracing through forward error correction additionally permits channel path trace through the WDM system, a particularly useful feature for complex system

topologies and WDM systems with extensive add/drop multiplexing or cross-connect features.

An exemplary encoder 45 is shown in greater detail in FIG. 3. Signals received from clock/data recovery circuit 43 are supplied to encoder 45 on input line 410. Serial-  
5 to-parallel converter circuit 412 converts the received serial data to parallel data. The output of serial-to-parallel converter circuit 412 is supplied on a plurality of lines 413 to FEC encoder core circuit 414, as described, for example, in U.S. Patent Application "Parallel Spectral Reed-Solomon Encoder and Decoder" to Neifeld et al., filed October 7, 1997, U.S. Application Serial No. 08/946,166, incorporated by reference herein. FEC  
10 encoder core circuit 414 encodes the received data in parallel in accordance with a Reed-Solomon code by attaching a plurality of syndrome symbols or groupings of bits followed by an inverse Fourier transform of the data and syndromes. FEC encoder core circuit 414 outputs encoded data in parallel to parallel-to-serial converter 416, which serializes the data for output to modulator drive 35.

15 Returning to FIG. 1, each information-bearing optical signal produced by a remodulator constitutes a channel in optical system 10, the wavelength of which corresponds to a channel selector wavelength. The optical signal channels output from remodulators 30 are brought together in optical combiner 50 for conveyance to optical waveguide 60. Optical combiner 50 is selected from any passive optical component  
20 which can combine plural wavelengths into a single output medium. Frequently, optical splitters used to divide a signal among plural outputs are used as optical combiners, operated in reverse fashion from the splitter. Exemplary optical combiners include 1 x N passive splitters available from Corning, Inc., Corning, NY, 1 x N wideband single mode

splitters available from IOT Integrierte Optik GmbH, Waghausel-Kirrlach, Germany, and fused fiber combiners available from Gould, Inc., Millersville, MD. The combination of channels forms a multiplexed optical signal which is output to waveguide 60. Optical waveguide 60 is typically a single-mode optical fiber such as SMF-28, available from  
5    Corning, and TRUEWAVE, available from AT&T Corp./Lucent Technologies, and is the principal transmission medium for the optical communication system. However, any optical waveguide which is capable of transporting multiple optical wavelengths can be employed as waveguide 60 in optical system 10.

Interposed along optical waveguide 60 are one or more optical amplifiers 70.  
10    Optical amplifiers 70 are selected from any device which directly increases the strength of plural optical signals without the need for optical-to-electrical conversion. In general, optical amplifiers 70 are selected from optical waveguides doped with rare earth ions such as erbium, neodymium, praseodymium, ytterbium, or mixtures thereof. Optical amplifiers, their materials, and their operation are further described in Gowar, Ed. Optical  
15    Communication Systems, incorporated by reference above and in Desurvire, Erbium-Doped Fiber Amplifiers, (John Wiley & Sons, Inc., NY), c. 1994, the disclosures of which are incorporated by reference herein. Exemplary optical amplifier configurations are described in the parent applications, the disclosures of which are incorporated by reference. Further descriptions of doped-fiber optical amplifier configurations suitable  
20    for use in the optical communication system of the present invention are described in Bjarklev, Optical Fiber Amplifiers: Design and System Applications, (Artech House, Norwood, MA) c. 1993, the disclosure of which is incorporated herein by reference.

Following transmission and amplification of the multiplexed optical signals along waveguide 60, a portion of the multiplexed optical signal must be sent to each of the remodulating channel selectors for selection and routing to an appropriate optical receiver. The multiplexed signal is input to optical splitter 90 which places a portion of the multiplexed signal onto plural output paths 92. Each output path 92 optically communicates with a remodulation channel selector 100. Optical splitter 90 is selected from any optical device which can divide an input optical signal and place it onto plural output paths. Exemplary splitters include passive optical components such as those components described for use as optical combiner 50. Splitter 90 in combination with remodulating channel selectors 100 constitute an exemplary wavelength demultiplexer.

FIG. 4 schematically depicts an exemplary remodulating channel selector 100 for use in WDM optical communication system 10. Remodulating channel selector 100 includes an optical input port 101 for receiving the WDM optical signal from splitter output path 92. The WDM optical signal traverses optical path 105 through splitter 103 to channel selector 102. Channel selector 102 passes optical signals having wavelengths other than the channel wavelength to be processed by the remodulating channel selector. These non-selected channels pass through low reflectivity port 104 and exit the optical communication system. The low reflectivity port 104 may be an angled fiber cut, although any low reflectivity waveguide termination technique may be employed. The selected channel wavelength is reflected by channel selector 102 through splitter 103 onto optical path 106. In an exemplary embodiment, optical splitter 103 is a fused fiber coupler and channel selector 102 comprises a Bragg grating member configured to reflect the selected channel wavelength. Preferably, the Bragg grating comprises a series of



photoinduced refractive index perturbations in an optical fiber which causes the reflection of optical signals within a selected wavelength band. Bragg gratings suitable for use in the optical system of the present invention are described in Morey et al., "Photoinduced Bragg Gratings in Optical Fibers," Optics and Photonics News, February 1994, pp. 8-14, 5 the disclosure of which is incorporated by reference herein.

Although a Bragg grating is depicted as the channel selecting element, it is understood that numerous other optical components can be employed as channel selector 102. Such optical components include, but are not limited to, multilayer interference filters, tunable Fabry-Perot selectors, and wavelength routers. In an exemplary 10 embodiment, the optical bandwidth is selected to be sufficiently narrow to minimize the deleterious effects of amplified spontaneous emission (ASE).

The selected optical channel is converted by electro-optical converter 108, typically a photodiode, to an electrical signal. The electrical signal is amplified by transimpedance amplifier 110 and routed through clock and data recovery circuit 112 for 15 retiming. In an exemplary embodiment, the electrical bandwidth of the optical-to-electrical converter and the transimpedance amplifier is selected to match the data rate of the incoming signal. Optionally, the remodulating channel selector includes FEC decoder 114 circuit for accurate reconstruction of the transmitted signal, as discussed above.

As shown in Fig. 5, FEC decoder 114 includes a serial-to-parallel converter 510, 20 and FEC decoder core circuit 512 and a parallel-to-serial converter circuit 514. Data from clock/data recovery circuit 112 is supplied to a serial-to-parallel converter 510, which supplies a parallel output to FEC decoder core circuit 512, as described, for example, in Neifeld et al., *supra*. As further described in Neifeld et al., FEC decoder core circuit 512

includes a Fourier transform circuit, Berlekamp algorithm circuit and Recursive Extension circuit (not shown). Received data is decoded by initially performing the Fourier transform. The data is next typically supplied to both a temporary memory and the Berlekamp algorithm circuit, which acts on the data in parallel to supply a parallel

5 output to the Recursive Extension circuit. The recursive extension circuit, also operates in parallel, to generate an error signal, which is compared with the received data stored in memory. As a result, errors which may have occurred during transmission, for example, are corrected. The resulting parallel output of FEC decoder core circuit 512 is supplied to parallel-to-serial conversion circuit 514 and passed to modulator 118. The parallel

10 construction of FEC decoder 114, as well as FEC encoder 45 described above, permits encoding and decoding of data at high speeds.

Returning to FIG. 4, direct modulation of optical transmitter 116 by way of modulator 118 will now be described. Although "modulator" 118 is depicted as a discrete device, in actuality it can consist of d.c. power supply 119 interconnected with an

15 electronic switch. The electronic switch in turn optically communicates with the electrical signal containing the information from the selected channel output through the optical-to-electrical converter and processed by the subsequent elements. The electronic switch controls the flow of current from the d.c. supply to the optical emitter in response to the information received from the electrical signal. Alternatively, the direct

20 modulation of the emitter can be performed using a voltage-controlled current source for the elements labeled 118 and 119 in FIG. 3. Such a current source for the optical emitter provides a current whose magnitude is directly related to the applied voltage. The applied

voltage represents the information received from the optical-to electrical converter; alternatively the current may be directly derived from the modulating voltage.

Optical transmitter 116 is selected from a variety of optical devices, depending upon the optical interface required for receiver 130. When the signal emitted by the remodulating channel selector is destined for long distance transmission (e.g., through the optical combiner of a further WDM optical system as depicted in FIG. 1), the optical emitter is selected to be a DFB laser. When the signal emitted by the remodulating channel selector is destined for an adjacent receiver, the optical emitter within the optical transmitter is selected from lower-cost, shorter-range optical emitters such as Fabry-Perot lasers, light-emitting diodes, and superluminescent diodes.

The wavelength of the optical emitter employed in optical transmitter 116 can be the same wavelength as the wavelength of the optical channel selected by the particular channel selector or it can be a different wavelength. When the optical channel is output directly to a receiver, the wavelength of the optical signal is not critical. In such an embodiment, the same wavelength can be output by all of the optical transmitters 116. Since an optical signal being output directly to an optical receiver need not be optically amplified, the optical emitter can be selected to have any wavelength detectable by the optical receiver (e.g., a wavelength outside the gain band of rare-earth doped fiber amplifiers such as 1310 nm). However, if the optical signal emitted by the remodulating channel selector is destined for transmission in the same or another WDM system, then the wavelength of the optical emitter is selected to be compatible with the channel plan of that system. For example, the optical emitter may create a signal having the same wavelength as the selected optical signal, or it may produce an optical signal having a

wavelength which corresponds to another channel from the input WDM optical signal. If the remodulating channel selectors are incorporated into a switching matrix, a variable wavelength optical emitter can be used to dynamically select an available wavelength within a WDM optical channel plan.

- 5           In an alternate embodiment (not shown) the optical signal emitter is externally modulated, e.g., as in the remodulators of FIG. 2. External modulation is particularly advantageous when the signal output by the remodulating channel selector is destined for long-distance transmission. In such an embodiment, the remodulating channel selectors can serve to reshape and retune an optical signal, e.g., an optical signal which has
- 10 traversed the maximum dispersion-limited transmission distance (e.g., a distance of approximately 600 km for optical fibers such as SMF-28).

In this manner, a modulated optical signal is output by optical transmitter 116 through remodulating channel selector output port 113. The remodulating channel selector output signal is transmitted to optical receiver 130. Receiver 130 generally

15 detects the optical signal and converts it to an electrical signal, typically through the use of a photodiode device. Various optical receivers suitable for use in optical system 10 are described in Goward, Optical Communication Systems, discussed above. In optical communication system 10, receiver 130 will frequently be part of an existing optical communication system to which the remodulated optical signal is routed. Consequently,

20 the optical system 10 can function with numerous types of receivers to ensure compatibility with existing optical equipment. In particular, the presence of remodulating channel selectors 100 enables the WDM optical communication system to communicate with optical receivers conforming to the SONET "short-haul" standard. Further

descriptions of SONET interface standards are found in SONET Transport Systems: Common Criteria, (GR-253-CORE, Issue 1, December, 1994), the disclosure of which is incorporated by reference herein.

Alternatively, as depicted in FIG. 1, the output of a remodulating channel selector  
5 is conveyed to another WDM optical system or a portion of the same WDM optical system through input to an optical combiner for multiplexing with other optical signals or routing, e.g., through an add/drop multiplexer.

Optionally, channel selectors 120 are provided for selecting an optical channel from an input WDM optical signal. Such channel selectors, described in more detail in  
10 the parent applications incorporated by reference above, select an optical channel and directly output the selected channel without remodulation. Such channel selectors are used particularly when the optical receivers with which they communicate conform to the SONET "long-haul" standard. Such "non-remodulating" channel selectors can also route their selected optical channels to an optical combiner for further transmission in the same  
15 WDM optical system or in a different WDM optical system.

While the foregoing invention has been described in terms of the embodiments discussed above, numerous variations are possible. Accordingly, modifications and changes such as those suggested above, but not limited thereto, are considered to be within the scope of following claims.

**WHAT IS CLAIMED IS:**

1. An optical device comprising:
  - a photodetector circuit receiving first optical signals and outputting first serial electrical signals in response thereto;
  - 5 a serial-to-parallel conversion circuit coupled to said photodetector and receiving said first serial electrical signals, said serial-to-parallel conversion circuit outputting said first electrical signals in parallel;
  - a forward error correction encoder circuit coupled to said serial-to-parallel conversion circuit and being configured to receive said first electrical signals in parallel,
  - 10 said encoder circuit encoding said first electrical signals in accordance with a code to generate parallel second electrical signals;
  - a parallel-to-serial conversion circuit coupled to said forward error correction encoder circuit and receiving said parallel second electrical signals, said parallel-to-serial conversion circuit outputting said second electrical signals in a serial fashion; and
  - 15 an optical emitter coupled to said parallel-to-serial conversion circuit and receiving said serial second electrical signals, said optical emitter outputting second optical signals in accordance with said second electrical signals.
2. An optical device in accordance with claim 1, wherein said first optical signals are at a first wavelength and said second optical signals are at a second  
20 wavelength.
3. An optical device in accordance with claim 1, further comprising a clock and data recovery circuit coupled between said photodetector and said serial-to-parallel conversion circuit.

4. An optical device in accordance with claim 1, wherein said code is a Reed-Solomon code.

5. An optical device in accordance with claim 1, wherein said forward error correction encoder circuit encodes said first electrical signals in a frequency domain.

5 6. An optical device comprising:

a photodetector circuit receiving first optical signals and outputting first electrical signals in response thereto;

a serial-to-parallel conversion circuit coupled to said photodetector and receiving said first electrical signals, said serial-to-parallel conversion circuit outputting said first  
10 electrical signals in parallel;

a forward error correction decoder circuit coupled to said serial-to-parallel conversion circuit and being configured to receive said first electrical signals in parallel, said forward error correction decoder circuit decoding said first encoded electrical signals in accordance with a code to generate parallel second electrical signals;

15 a parallel-to-serial conversion circuit coupled to said forward error correction decoder circuit and receiving said second electrical signals, said parallel-to-serial conversion circuit outputting said second electrical signals in a serial fashion; and

an optical emitter coupled to said parallel-to-serial conversion circuit and receiving said serial second electrical signals, said optical emitter outputting second  
20 optical signals in accordance with said second electrical signals.

7. An optical device in accordance with claim 6, wherein said first optical signals are at a first wavelength and said second optical signals are at a second wavelength.

8. An optical device in accordance with claim 6, further comprising a clock and data recovery circuit coupled between said photodetector circuit and said serial-to-parallel conversion circuit.

9. An optical device in accordance with claim 6, wherein said code is a Reed-  
5 Solomon code.

10. An optical device in accordance with claim 6, wherein said forward error correction decoder circuit decodes said first electrical signals in a frequency domain.

11. An optical device comprising:  
a first photodetector circuit receiving first optical signals and outputting first  
10 electrical signals in response thereto;  
a first serial-to-parallel conversion circuit coupled to said first photodetector and receiving said first electrical signals, said first serial-to-parallel conversion circuit outputting said first electrical signals in parallel;  
a forward error correction encoder circuit coupled to said first serial-to-parallel  
15 conversion circuit and being configured to receive said first electrical signals in parallel, said forward error correction encoder circuit encoding said first electrical signals in accordance with a code to generate parallel second electrical signals;  
a first parallel-to-serial conversion circuit coupled to said forward error correction encoder circuit and receiving said parallel second electrical signals, said first parallel-to-  
20 serial conversion circuit outputting said second electrical signals in a serial manner;  
a first optical emitter coupled to said parallel-to-serial conversion circuit and receiving said second electrical signals, said optical emitter configured to supply second



optical signals to an optical communication path in accordance with said second electrical signals;

a second photodetector circuit configured to be coupled to said optical communication path receiving said second optical signals and outputting third electrical signals in response thereto;

a second serial-to-parallel conversion circuit coupled to said second photodetector and receiving said third optical signals, said second serial-to-parallel conversion circuit outputting said third electrical signals in parallel;

a forward error correction decoder circuit coupled to said second serial-to-parallel conversion circuit and being configured to receive said third electrical signals in parallel, said forward error correction decoder circuit decoding said third electrical signals in accordance with said code to generate parallel fourth electrical signals;

a second parallel-to-serial conversion circuit coupled to said forward error correction decoder circuit and receiving said fourth electrical signals, said parallel-to-serial conversion circuit outputting said fourth electrical signals in a serial fashion; and

a second optical emitter coupled to said parallel-to-serial conversion circuit and receiving said serial fourth electrical signals, said second optical emitter outputting third optical signals in accordance with said serial fourth electrical signals.

12. An optical device in accordance with claim 11, wherein said first optical signals and said second optical signals are at different wavelengths.

13. An optical device in accordance with claim 11, wherein said second optical signals and said third optical signals are at different wavelengths.

14. An optical device in accordance with claim 11, further comprising:

a first clock and data recovery circuit coupled between said first photodetector circuit and said first serial-to-parallel conversion circuit; and

a second clock and data recovery circuit coupled between said second photodetector circuit and said second serial-to parallel conversion circuit.

5           15.    An optical device in accordance with claim 11, wherein said code is a Reed-Solomon code.

          16.    An optical device in accordance with claim 11, wherein said forward error correction encoder circuit encodes said first electrical signals and said forward error correction decoder decodes said third electrical signals in a frequency  
10   domain.

          17.    An optical communication device comprising:  
          a plurality of encoder circuits each receiving respective electrical data signals and outputting encoded electrical signals in accordance with a Reed-Solomon code;  
          a plurality of optical emitters, each emitting light at a respective wavelength and  
15   each coupled to a respective one of said plurality of encoder circuits, each of said optical emitters outputting optical signals in accordance with said encoded electrical signals; and  
          an optical multiplexer coupled to each of said plurality of optical emitters, said optical multiplexer being configured to receive said optical signals from said plurality of optical emitters and supply said optical signals on an optical communication path.

20           18.    An optical communication device, comprising:  
          an optical demultiplexer having an input configured to be coupled to an optical communication path, said optical communication path carrying a plurality of optical

channels, each at a respective wavelength, said optical demultiplexer further having a plurality of outputs, each supplying a respective one of said optical channels;

a plurality of photodetectors, each respectively coupled to one of said plurality of outputs of said optical demultiplexers, each of said plurality of photodetectors generating  
5 first electrical signals in response to said respective one of said plurality of optical channels; and

a plurality of forward error correction decoders, each respectively coupled to one of said plurality of photodetectors, each of said plurality of forward error correction decoders decoding said first electrical signals in accordance with a Reed-Solomon code  
10 to generate second electrical signals.

19. An optical communication device comprising:

a plurality of encoder circuits each receiving respective first electrical signals and outputting encoded second electrical signals in accordance with a Reed-Solomon code;

a plurality of optical emitters, each emitting a respective one of a plurality of  
15 optical channels, each of said optical channels being at a respective wavelength, and each of said plurality of optical emitters being coupled to a respective one of said plurality of encoder circuits, said optical emitters outputting said plurality of optical channels in accordance with said encoded electrical signals;

an optical multiplexer coupled to each of said plurality of optical emitters, said  
20 optical multiplexer being configured to receive said optical signals from said plurality of optical emitters and supply said optical signals to an optical communication path.

an optical demultiplexer having an input configured to be coupled to said optical communication path, said optical demultiplexer further having a plurality of outputs, each supplying a respective one of said optical channels;

5 a plurality of photodetectors, each respectively coupled to one of said plurality of outputs of said optical demultiplexers, each of said plurality of photodetectors generating third electrical signals in response to said respective one of said plurality of optical channels; and

a plurality of forward error correction decoders, each respectively coupled to one of said plurality of photodetectors, each of said plurality of forward error correction  
10 decoders decoding said third electrical signals in accordance with a Reed-Solomon code to generate fourth electrical signals.

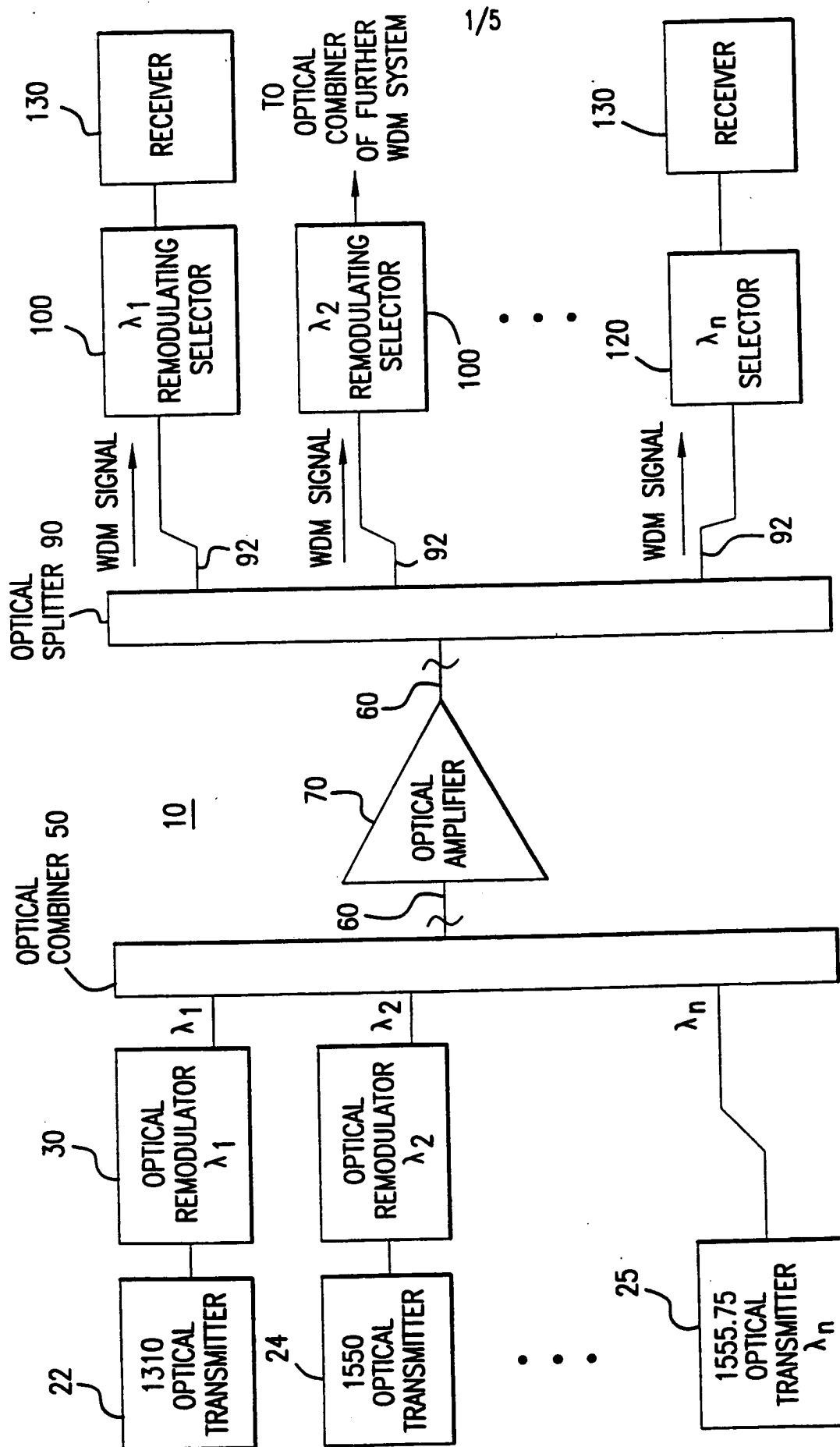
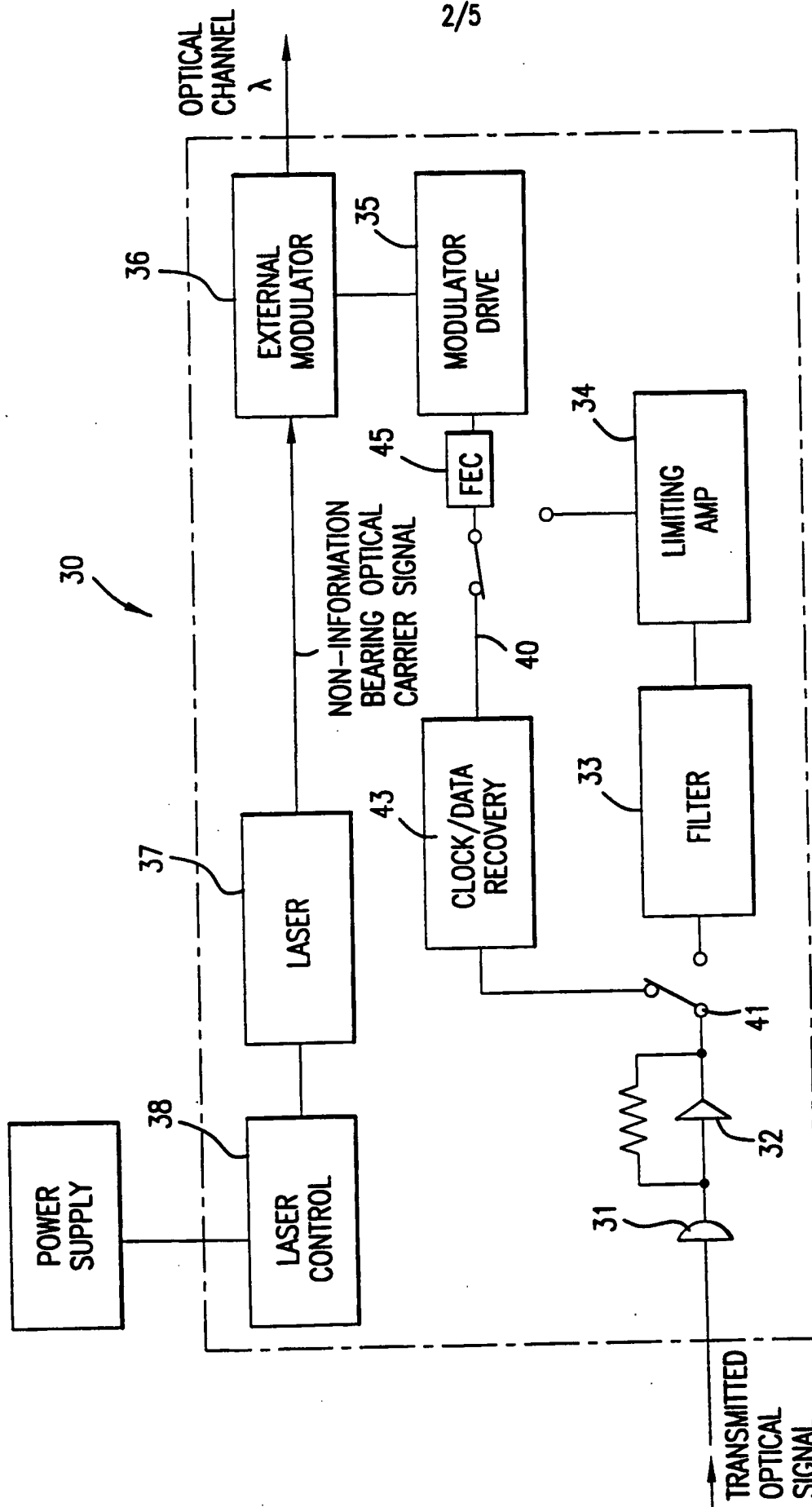


FIG.1



**FIG. 2**

3/5

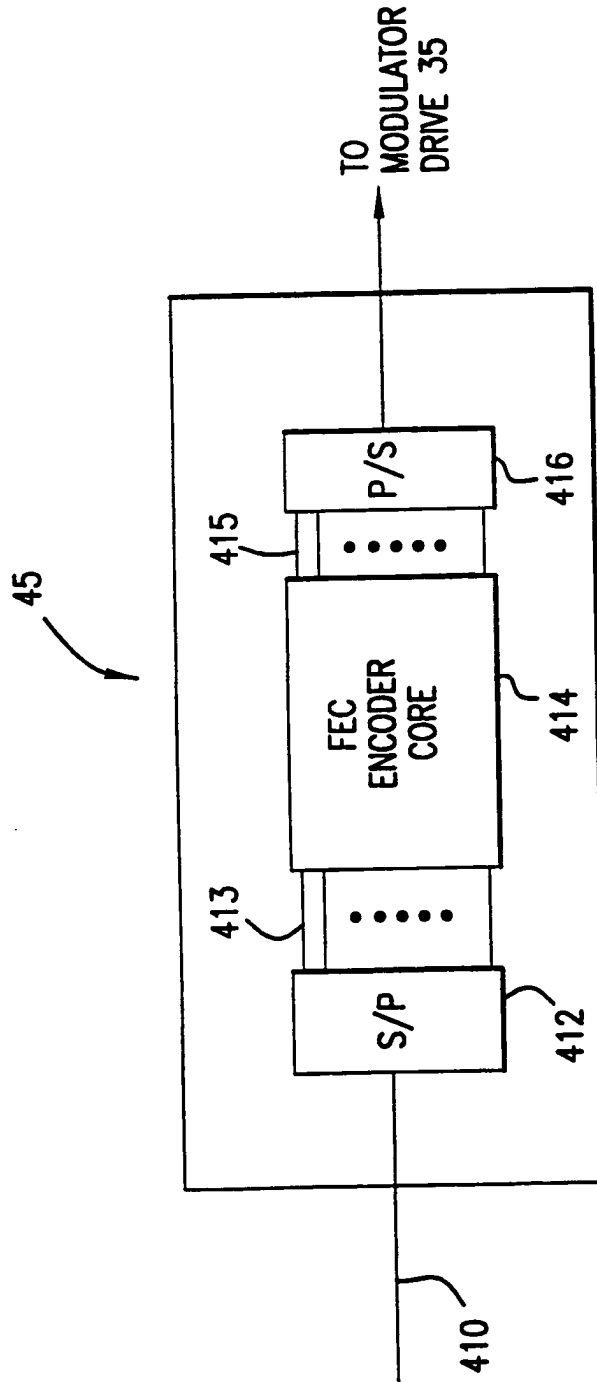


FIG.3

4/5

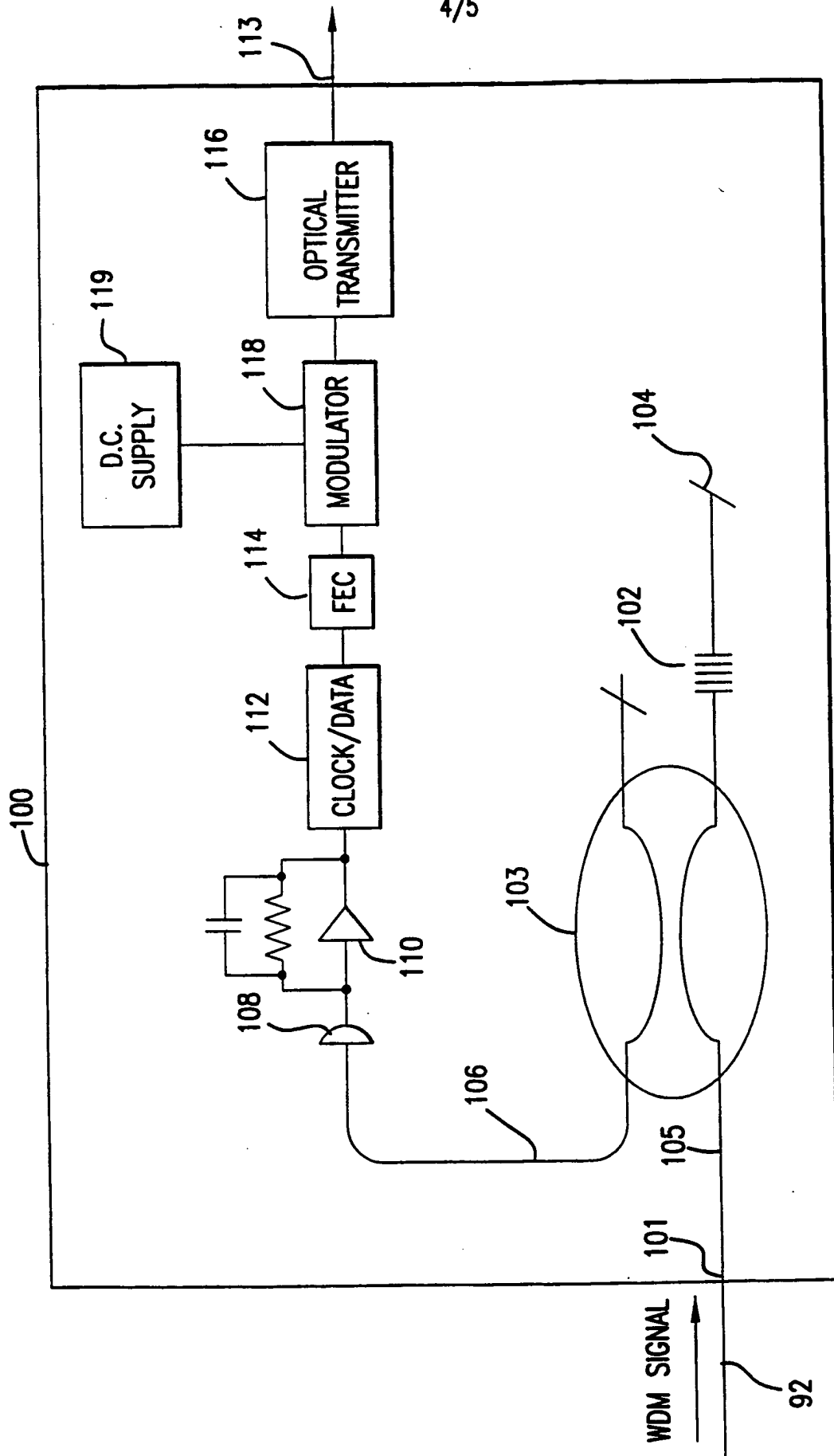


FIG.4



5/5

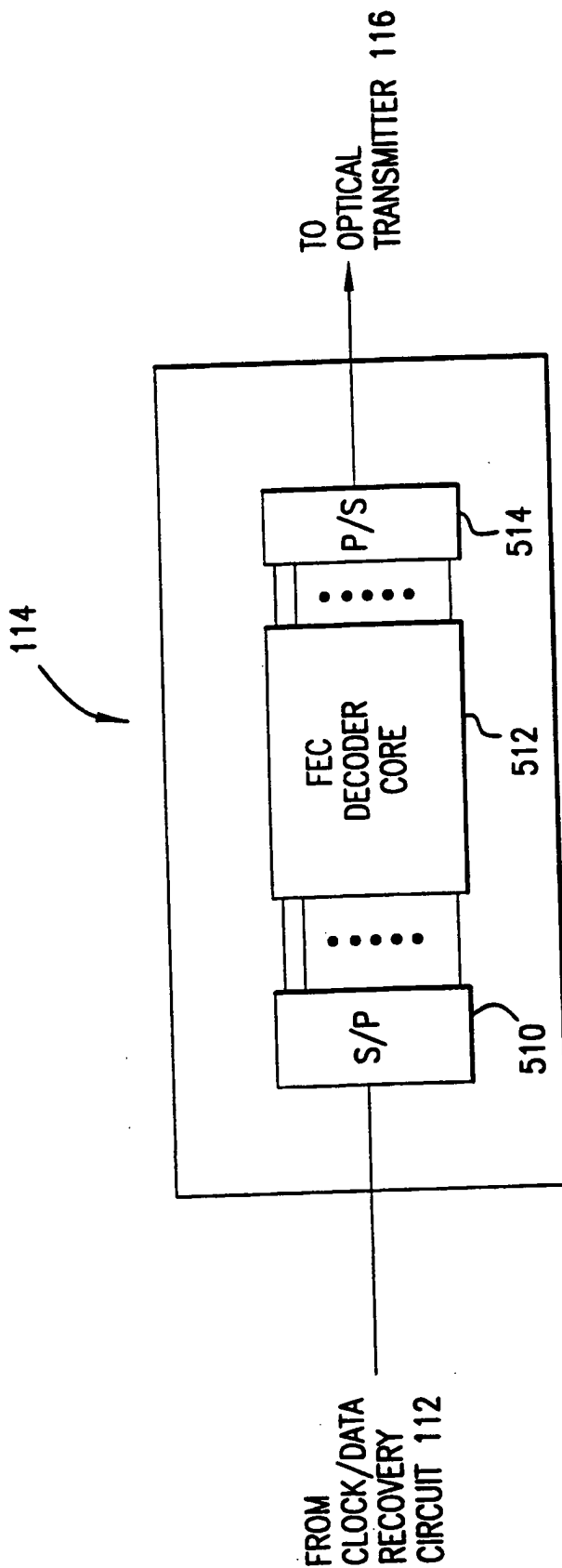


FIG.5

## INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 98/22273

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 6 H04J14/02 H04B10/16 H04L1/00

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H04J H04B H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TOMIZAWA M ET AL: "FORWARD ERROR CORRECTING CODES IN SYNCHRONOUS FIBER OPTIC TRANSMISSION SYSTEMS" JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 15, no. 1, January 1997, pages 43-51, XP000642276 see abstract see page 44, column 1, line 36 - column 2, line 12	1,3-6, 8-11, 14-16
Y	see page 45, column 2, line 5 - page 46, column 1, line 12 --- -/--	2,7,12, 13,17-19

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

## \* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search

15 February 1999

Date of mailing of the international search report

25/02/1999

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Chauvet, C

# INTERNATIONAL SEARCH REPORT

Inter national Application No

PCT/US 98/22273

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 504 609 A (ALEXANDER STEPHEN B ET AL) 2 April 1996 cited in the application see abstract see column 1, line 40 - line 58 see column 2, line 28 - column 3, line 5 see column 3, line 21 - column 6, line 8	2,7,12, 13,17-19
A	see column 7, line 21 - line 65	1,3-6, 8-11, 14-16
A	<p style="text-align: center;">---</p> JEONG G ET AL: "LONG-DISTANCE PARALLEL DATA LINK USING WDM TRANSMISSION WITH BIT-SKEW COMPENSATION" JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 14, no. 5, 1 May 1996, pages 655-660, XP000598716 see abstract see page 656, column 2, line 10 - page 657, column 1, line 15	1-19
A	<p style="text-align: center;">---</p> SHOU-KUO SHAO ET AL: "WDM CODING FOR HIGH-CAPACITY LIGHTWAVE SYSTEMS" JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 12, no. 1, 1 January 1994, pages 137-148, XP000460016 see abstract see page 137, column 2, line 1 - line 21 see page 138, column 1, line 5 - column 2, line 10	1-19
A	<p style="text-align: center;">---</p> SIAN S ET AL: "40GBIT/S (16 X 2.5GBIT/S) UNREPEATERED TRANSMISSION OVER 427KM" ELECTRONICS LETTERS, vol. 32, no. 1, 4 January 1996, page 50/51 XP000553374	1-16
X	see page 50, column 1 - column 2, line 3	17-19

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 98/22273

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5504609 A	02-04-1996	US 5726784 A	10-03-1998
		US 5784184 A	21-07-1998
		US 5715076 A	03-02-1998
<hr/>			